DUAL SPIN VALVE SENSOR WITH A LONGITUDINAL BIAS STACK

CROSS REFERENCE TO RELATED APPLICATION

U.S. patent application docket number SJO9-2001-00112US1,

5 entitled DUAL MAGNETIC TUNNEL JUNCTION SENSOR WITH A LONGITUDINAL

BIAS STACK, was filed on the same day, owned by a common assignee

and having the same inventors as the present invention.

BACKGROUND OF THE INVENTION

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1. Field of the Invention

This invention relates in general to spin valve magnetic

transducers for reading information signals from a magnetic

medium and, in particular, to a dual spin valve sensor with a

15 longitudinal bias stack between first and second spin valve

stacks of the dual sensor.

2. Description of the Related Art

Computers often include auxiliary memory storage devices

20 having media on which data can be written and from which data can

be read for later use. A direct access storage device (disk

drive) incorporating rotating magnetic disks is commonly used for

storing data in magnetic form on the disk surfaces. Data is

recorded on concentric, radially spaced tracks on the disk

surfaces. Magnetic heads including read sensors are then used to read data from the tracks on the disk surfaces.

In high capacity disk drives, magnetoresistive (MR) read sensors, commonly referred to as MR sensors, are the prevailing
5 read sensors because of their capability to read data from a surface of a disk at greater track and linear densities than thin film inductive heads. An MR sensor detects a magnetic field through the change in the resistance of its MR sensing layer (also referred to as an "MR element") as a function of the
10 strength and direction of the magnetic flux being sensed by the MR layer.

The conventional MR sensor operates on the basis of the anisotropic magnetoresistive (AMR) effect in which an MR element resistance varies as the square of the cosine of the angle
15 between the magnetization in the MR element and the direction of sense current flowing through the MR element. Recorded data can be read from a magnetic medium because the external magnetic field from the recorded magnetic medium (the signal field) causes a change in the direction of magnetization in the MR element,
20 which in turn causes a change in resistance in the MR element and a corresponding change in the sensed current or voltage.

Another type of MR sensor is the giant magnetoresistance (GMR) sensor manifesting the GMR effect. In GMR sensors, the resistance of the MR sense layer varies as a function of the
25 spin-dependent transmission of the conduction electrons between

magnetic layers separated by a non-magnetic spacer layer and the accompanying spin-dependent scattering which takes place at the interface of the magnetic and nonmagnetic layers and within the magnetic layers.

5   GMR sensors using only two layers of ferromagnetic material (e.g., Ni-Fe) separated by a layer of nonmagnetic material (e.g., copper) are generally referred to as spin valve (SV) sensors manifesting the SV effect.

Fig. 1 shows a prior art SV sensor 100 comprising end 10 regions 104 and 106 separated by a central region 102. A first ferromagnetic layer, referred to as a pinned (or reference) layer 120, has its magnetization typically fixed (pinned) by exchange coupling with an antiferromagnetic (AFM) layer 125. The magnetization of a second ferromagnetic layer, referred to as a 15 free (or sense) layer 110, is not fixed and is free to rotate in response to the magnetic field from the recorded magnetic medium (the signal field). The free layer 110 is separated from the pinned layer 120 by a nonmagnetic, electrically conducting spacer layer 115. Hard bias layers 130 and 135 formed in the end 20 regions 104 and 106, respectively, provide longitudinal bias fields for stabilizing the free layer 110. Leads 140 and 145 formed on hard bias layers 130 and 135, respectively, provide electrical connections for sensing the resistance of SV sensor 100. In the SV sensor 100, because the sense current flow 25 between the leads 140 and 145 is in the plane of the SV sensor

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layers, the sensor is known as a current-in-plane (CIP) SV sensor. IBM's U.S. Patent No. 5,206,590 granted to Dieny et al., incorporated herein by reference, discloses a SV sensor operating on the basis of the GMR effect.

5   Another type of GMR sensor is an antiparallel (AP)-pinned SV sensor. The AP-pinned SV sensor differs from the simple SV sensor in that an AP-pinned structure has multiple thin film layers instead of a single pinned layer. The AP-pinned structure has an antiparallel coupling (APC) layer sandwiched between first

10 and second ferromagnetic pinned layers. The first pinned layer has its magnetization oriented in a first direction by exchange coupling to the antiferromagnetic (AFM) pinning layer. The second pinned layer is immediately adjacent to the free layer and is antiparallel exchange coupled to the first pinned layer

15 because of the minimal thickness (in the order of 8 Å) of the APC layer between the first and second pinned layers. Accordingly, the magnetization of the second pinned layer is oriented in a second direction that is antiparallel to the direction of the magnetization of the first pinned layer.

20   The AP-pinned structure is preferred over the single pinned layer because the magnetizations of the first and second pinned layers of the AP-pinned structure subtractively combine to provide a net magnetization that is much less than the magnetization of the single pinned layer. The direction of the

25 net magnetization is determined by the thicker of the first and

second pinned layers. A reduced net magnetization equates to a reduced demagnetization field from the AP-pinned structure. Since the antiferromagnetic exchange coupling is inversely proportional to the net magnetization, this increases exchange

5 coupling between the first pinned layer and the antiferromagnetic pinning layer. The AP-pinned SV sensor is described in commonly assigned U.S. Patent No. 5,465,185 to Heim and Parkin which is incorporated by reference herein.

Another type of magnetic device currently under development

10 is a magnetic tunnel junction (MTJ) device. The MTJ device has potential applications as a memory cell and as a magnetic field sensor. The MTJ device comprises two ferromagnetic layers separated by a thin, electrically insulating, tunnel barrier layer. The tunnel barrier layer is sufficiently thin that

15 quantum-mechanical tunneling of charge carriers occurs between the ferromagnetic layers. The tunneling process is electron spin dependent, which means that the tunneling current across the junction depends on the spin-dependent electronic properties of the ferromagnetic materials and is a function of the relative

20 orientation of the magnetizations of the two ferromagnetic layers. In the MTJ sensor, one ferromagnetic layer has its magnetization fixed, or pinned, and the other ferromagnetic layer has its magnetization free to rotate in response to an external magnetic field from the recording medium (the signal field).

25 When an electric potential is applied between the two

ferromagnetic layers, the sensor resistance is a function of the
tunneling current across the insulating layer between the
ferromagnetic layers. Since the tunneling current that flows
perpendicularly through the tunnel barrier layer depends on the

5 relative magnetization directions of the two ferromagnetic
layers, recorded data can be read from a magnetic medium because
the signal field causes a change of direction of magnetization of
the free layer, which in turn causes a change in resistance of
the MTJ sensor and a corresponding change in the sensed current

10 or voltage. IBM's U.S. Patent No. 5,650,958 granted to Gallagher
et al., incorporated in its entirety herein by reference,
discloses an MTJ sensor operating on the basis of the magnetic
tunnel junction effect.

Fig. 2 shows a prior art MTJ sensor 200 comprising a first

15 electrode 204, a second electrode 202, and a tunnel barrier layer
215. The first electrode 204 comprises a pinned layer
(ferromagnetic pinned layer) 220, an antiferromagnetic (AFM)
pinning layer 230, and a seed layer 240. The magnetization of
the pinned layer 220 is fixed through exchange coupling with the

20 AFM layer 230. The second electrode 202 comprises a free layer
(ferromagnetic free layer) 210 and a cap layer 205. The free
layer 210 is separated from the pinned layer 220 by a
nonmagnetic, electrically insulating tunnel barrier layer 215.
In the absence of an external magnetic field, the free layer 210

25 has its magnetization oriented in the direction shown by arrow

212, that is, generally perpendicular to the magnetization direction of the pinned layer 220 shown by arrow 222 (tail of an arrow pointing into the plane of the paper). A first lead 260 and a second lead 265 formed in contact with first electrode 204

5 and second electrode 202, respectively, provide electrical connections for the flow of sensing current I_s from a current source 270 to the MTJ sensor 200. Because the sensing current is perpendicular to the plane of the sensor layers, the MTJ sensor 200 is known as a current-perpendicular-to-plane (CPP) sensor. A

10 signal detector 280, typically including a recording channel such as a partial-response maximum-likelihood (PRML) channel, connected to the first and second leads 260 and 265 senses the change in resistance due to magnetization changes induced in the free layer 210 by the external magnetic field.

15   Two types of current-perpendicular-to-plane (CPP) sensors have been extensively explored for magnetic recording at ultrahigh densities ($\geq$ 20 Gb/in^2). One is a GMR spin valve sensor and the other is a MTJ sensor. Two challenging issues are encountered when the CPP sensor is used for ever increasing

20 magnetic recording densities. First, the GMR coefficient may not be high enough to ensure adequate signal amplitude as the sensor width is decreased and second, magnetic stabilization of the sense layer can be difficult due to the use of insulating layers to avoid current shorting around the active region of the sensor.

A dual CPP sensor can be used to provide increased magnetoresistive response to a signal field due to the additive response of the two sensors. IBM's U.S. Patent No. 5,287,238 granted to Baumgart et al. discloses a dual CIP SV sensor.
5 However, sensor stability still remains a major concern.

There is a continuing need to increase the GMR coefficient and reduce the thickness of GMR sensors while improving sensor stability. An increase in the GMR coefficient and reduced sensor geometry equates to higher bit density (bits/square inch of the
10 rotating magnetic disk) read by the read head.

SUMMARY OF THE INVENTION

It is an object of the present invention to disclose a dual current-perpendicular-to-plane (CPP) spin valve (SV) sensor with
15 improved sensor layer stabilization.

It is another object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack between a first SV stack and a second SV stack to provide improved stabilization of the sense (free) layers of the first and second
20 SV stacks.

It is a further object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack comprising a first decoupling layer, a first ferromagnetic (FM1) layer, an antiferromagnetic (AFM) layer, a second ferromagnetic (FM2) layer

and a second decoupling layer disposed between the sense layers of first and second SV stacks.

It is yet another object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack

5 disposed between first and second SV stacks to provide three flux closures for improved sensor stability. A first flux closure provides stability of the first SV stack, a second flux closure provides stability of the second SV stack, and a third flux closure provides cancellation of demagnetizing fields from first

10 and second antiparallel (AP)-pinned layers of the dual SV sensor.

In accordance with the principles of the present invention, there is disclosed a preferred embodiment of the present invention wherein a dual CPP SV sensor comprises a first SV stack, a second SV stack and a longitudinal bias stack disposed

15 between first and second sense layers of the dual SV sensor. The first SV stack comprises a first antiferromagnetic (AFM1) layer, a first AP-pinned layer, a first conductive spacer layer and a first sense layer. The second SV stack comprises a second antiferromagnetic (AFM2) layer, a second AP-pinned layer, a

20 second conductive spacer layer and a second sense layer. The longitudinal bias stack comprises a third antiferromagnetic (AFM3) layer sandwiched between a first ferromagnetic (FM1) layer and a second ferromagnetic (FM2) layer, and first and second decoupling layers in laminar contact with the FM1 and FM2 layers,

25 respectively.

The AFM1 and AFM2 layers are set by annealing the SV sensor
at elevated temperature (about 280° C) in a large magnetic field
(about 10,000 Oe) oriented in a transverse direction
perpendicular to an air bearing surface (ABS) to orient the

5 magnetizations of the first and second AP-pinned layers. The
AFM3 layer, formed of antiferromagnetic material having a lower
blocking temperature (temperature at which the pinning field
reaches zero Oe) than AFM1 and AFM2, is set by the annealing but
is reset by a second annealing step at a lower temperature (about

10 240° C) in a much smaller magnetic field (about 200 Oe) oriented
in a longitudinal direction parallel to the ABS to reorient the
magnetizations of the FM1 and FM2 layers from the transverse to
the longitudinal direction without reorienting magnetizations of
the first and second AP-pinned layers. After the two annealing

15 steps, the magnetizations of the first and second AP-pinned
layers are oriented perpendicular to the ABS with net magnetic
moments canceling each other, and the magnetizations of the FM1
and FM2 layers are oriented in the longitudinal direction. The
magnetization of the FM1 layer forms a flux closure with the

20 magnetization of the first sense layer and the magnetization of
the FM2 layer forms a flux closure with the magnetization of the
second sense layer. The first and second sense layers can be
stabilized through magnetostatic interactions induced from the
first and second flux closures, respectively.

The above as well as additional objects, features, and advantages of the present invention will become apparent in the following detailed description.

5   BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and advantages of the present invention, as well as the preferred mode of use, reference should be made to the following detailed description read in conjunction with the accompanying drawings. In the
10 following drawings, like reference numerals designate like or similar parts throughout the drawings.

Fig. 1 is an air bearing surface view, not to scale, of a prior art SV sensor;

Fig. 2 is an air bearing surface view, not to scale, of a
15 prior art magnetic tunnel junction sensor;

Fig. 3 is a simplified diagram of a magnetic recording disk drive system using the dual CPP SV sensor of the present invention;

Fig. 4 is a vertical cross-section view, not to scale, of a
20 "piggyback" read/write head;

Fig. 5 is a vertical cross-section view, not to scale, of a "merged" read/write head;

Fig. 6 is an air bearing surface view, not to scale, of a preferred embodiment of a dual CPP SV sensor according to the
25 present invention;

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Fig. **7** is an air bearing surface view, not to scale, of another embodiment of a dual CPP SV sensor according to the present invention; and

Fig. **8** is an air bearing surface view, not to scale, of an embodiment of a hybrid SV/MTJ sensor according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The following description is the best embodiment presently contemplated for carrying out the present invention. This description is made for the purpose of illustrating the general principles of the present invention and is not meant to limit the inventive concepts claimed herein.

Referring now to Fig. **3**, there is shown a disk drive **300** embodying the present invention. As shown in Fig. **3**, at least one rotatable magnetic disk **312** is supported on a spindle **314** and rotated by a disk drive motor **318**. The magnetic recording media on each disk is in the form of an annular pattern of concentric data tracks (not shown) on the disk **312**.

At least one slider **313** is positioned on the disk **312**, each slider **313** supporting one or more magnetic read/write heads **321** where the head **321** incorporates the dual SV sensor of the present invention. As the disks rotate, the slider **313** is moved radially in and out over the disk surface **322** so that the heads **321** may access different portions of the disk where desired data are

recorded. Each slider **313** is attached to an actuator arm **319** by

means of a suspension **315**. The suspension **315** provides a slight

spring force which biases the slider **313** against the disk surface

322. Each actuator arm **319** is attached to an actuator **327**. The

5 actuator as shown in Fig. **3** may be a voice coil motor (VCM). The

VCM comprises a coil movable within a fixed magnetic field, the

direction and speed of the coil movements being controlled by the

motor current signals supplied by a controller **329**.

During operation of the disk storage system, the rotation of

10 the disk **312** generates an air bearing between the slider **313** (the

surface of the slider **313** which includes the head **321** and faces

the surface of the disk **312** is referred to as an air bearing

surface (ABS)) and the disk surface **322** which exerts an upward

force or lift on the slider. The air bearing thus

15 counterbalances the slight spring force of the suspension **315** and

supports the slider **313** off and slightly above the disk surface

by a small, substantially constant spacing during normal

operation.

The various components of the disk storage system are

20 controlled in operation by control signals generated by the

control unit **329**, such as access control signals and internal

clock signals. Typically, the control unit **329** comprises logic

control circuits, storage chips and a microprocessor. The

control unit **329** generates control signals to control various

25 system operations such as drive motor control signals on line **323**

and head position and seek control signals on line **328**. The
control signals on line **328** provide the desired current profiles
to optimally move and position the slider **313** to the desired data
track on the disk **312**. Read and write signals are communicated

5 to and from the read/write heads **321** by means of the recording
channel **325**. Recording channel **325** may be a partial response
maximum likelihood (PMRL) channel or a peak detect channel. The
design and implementation of both channels are well known in the
art and to persons skilled in the art. In the preferred

10 embodiment, the recording channel **325** is a PMRL channel.

The above description of a typical magnetic disk storage
system, and the accompanying illustration of Fig. **3** are for
representation purposes only. It should be apparent that disk
storage systems may contain a large number of disks and actuator

15 arms, and each actuator arm may support a number of sliders.

Fig. **4** is a side cross-sectional elevation view of a
"piggyback" read/write head **400**, which includes a write head
portion **402** and a read head portion **404**, the read head portion
employing a dual SV sensor **406** according to the present

20 invention. The SV sensor **406** is sandwiched between ferromagnetic
first and second shield layers **412** and **414** at the ABS **440**. A
nonmagnetic insulating layer **409** is sandwiched between the first
and second shield layers **412** and **414** in the region behind the
sensor extending away from the ABS to prevent shorting between

25 the shield layers. In response to external magnetic fields, the

resistance of the SV sensor **406** changes. A sense current I_s
conducted through the sensor causes these resistance changes to
be manifested as voltage changes. These voltage changes are then
processed as readback signals by the processing circuitry of the
5 data recording channel **346** shown in Fig. **3**.

   The write head portion **402** of the magnetic read/write head
400 includes a coil layer **416** sandwiched between first and second
insulating layers **418** and **420**. A third insulating layer **522** may
be employed for planarizing the head to eliminate ripples in the
10 second insulating layer **420** caused by the coil layer **416**. The
first, second and third insulating layers are referred to in the
art as an insulation stack. The coil layer **416** and the first,
second and third insulating layers **418, 420** and **422** are
sandwiched between first and second pole piece layers **424** and
15 **426**. The first and second pole piece layers **424** and **426** are
magnetically coupled at a back gap **428** and have first and second
pole tips **430** and **432** which are separated by a write gap layer
434 at the ABS **440**. An insulating layer **436** is located between
the second shield layer **414** and the first pole piece layer **424**.
20 Since the second shield layer **414** and the first pole piece layer
424 are separate layers, this read/write head is known as a
"piggyback" read/write head.

   Fig. **5** is the same as Fig. **4** except the second shield layer
514 and the first pole piece layer **524** are a common layer. This

type of read/write head is known as a "merged" head **500**. The insulation layer **436** of the piggyback head in Fig. **4** is omitted in the merged head **500** of Fig. **5**.

First Example

Fig. **6** shows an air bearing surface (ABS) view, not to scale, of a dual CPP spin valve (SV) sensor **600** according to a preferred embodiment of the present invention. The SV sensor **600** comprises end regions **604** and **606** separated from each other by a central region **602**. The seed layer **614** is a layer deposited to modify the crystallographic texture or grain size of the subsequent layers, and may not be needed depending on the subsequent layer. A first SV stack **608** deposited over the seed layer **614** comprises a first antiferromagnetic (AFM1) layer **616**, a first AP-pinned layer **617**, an conductive first spacer layer **624** and a first sense layer **625**. The first AP-pinned layer **617** is formed of two ferromagnetic layers **618** and **622** separated by an antiparallel coupling (APC) layer **620**. The APC layer is formed of a nonmagnetic material, preferably ruthenium (Ru), that allows the two ferromagnetic layers **618** and **622** to be strongly antiparallel-coupled together. The AFM1 layer **616** has a thickness at which the desired exchange properties are achieved, typically 100-300 Å.

A longitudinal bias stack 610 sequentially deposited over the first SV stack 608 comprises a first decoupling layer 629, a first ferromagnetic (FM1) layer 630, a third antiferromagnetic (AFM3) layer 632, a second ferromagnetic (FM2) layer 634 and a

5 second decoupling layer 633. A second SV stack 612 deposited over the longitudinal bias stack 610 comprises a second sense layer 639, a second conductive spacer layer 640, a second AP-pinned layer 641 and a second antiferromagnetic (AFM2) layer 648. The second AP-pinned layer 641 is formed of two

10 ferromagnetic layers 642 and 646 separated by an antiparallel coupling (APC) layer 644. The APC layer is formed of a nonmagnetic material, preferably ruthenium (Ru), that allows the two ferromagnetic layers 642 and 646 to be strongly anti-parallel coupled together. The AFM2 layer 648 has a thickness at which

15 the desired exchange properties are achieved, typically 100-300 Å. A cap layer 650, formed on the AFM2 layer 648, completes the central region 602 of the dual SV sensor 600.

The AFM1 layer 616 is exchange-coupled to the first AP-pinned layer 617 to provide a pinning field to pin the

20 magnetizations of the two ferromagnetic layers of the first AP-pinned layer perpendicular to the ABS as indicated by an arrow tail 619 and an arrow head 623 pointing into and out of the plane of the paper, respectively. The first sense layer 625 has a magnetization 627 that is free to rotate in the presence of an

external (signal) magnetic field. The magnetization **627** of the first sense layer **625** is preferably oriented parallel to the ABS in the absence of an external magnetic field.

The AFM2 layer **648** is exchange coupled to the second

5 AP-pinned layer **641** to provide a pinning magnetic field to pin the magnetizations of the two ferromagnetic layers of the second AP-pinned layer perpendicular to the ABS as indicated by an arrow head **643** and an arrow tail **645** pointing out of and into the plane of the paper, respectively. The second sense layer **639** has a

10 magnetization **637** that is free to rotate in the presence of an external (signal) magnetic field. The magnetization **637** of the second sense layer **639** is preferably oriented parallel to the ABS in the absence of an external magnetic field.

The AFM3 layer **632** is exchange coupled to the FM1 layer **630**

15 and the FM2 layer **634** to provide pinning fields to pin the magnetizations **631** and **635**, respectively, parallel to the plane of the ABS. The magnetizations **631** and **635** provide longitudinal bias fields which form flux closures with the first and second sense layers **625** and **639**, respectively, to stabilize the first

20 and second sense layers **625** and **639**.

First and second shield layers **652** and **654** adjacent to the seed layer **614** and the cap layer **650**, respectively, provide electrical connections for the flow of a sensing current I_s from a current source **660** to the SV sensor **600**. A signal detector **670**

which is electrically connected to the first and second shield

layers **652** and **654** senses the change in resistance due to changes

induced in the sense layers **625** and **639** by the external magnetic

field (e.g., field generated by a data bit stored on a disk).

5 The external field acts to rotate the magnetizations of the sense

layers **625** and **639** relative to the magnetizations of the pinned

layers **622** and **642** which are preferably pinned perpendicular to

the ABS. The signal detector **670** preferably comprises a partial

response maximum likelihood (PRML) recording channel for

10 processing the signal detected by SV sensor **600**. Alternatively,

a peak detect channel or a maximum likelihood channel (e.g., 1,7

ML) may be used. The design and implementation of the

aforementioned channels are known to those skilled in the art.

The signal detector **670** also includes other supporting

15 circuitries such as a preamplifier (electrically placed between

the sensor and the channel) for conditioning the sensed

resistance changes as is known to those skilled in the art.

The SV sensor **600** is fabricated in an integrated ion beam/DC

magnetron sputtering system to sequentially deposit the

20 multilayer structure shown in Fig. **6**. The sputter deposition

process is carried out in the presence of a longitudinal magnetic

field of about 40 Oe. The first shield layer **652** formed of Ni-Fe

having a thickness of 10000 Å is deposited on a substrate **601**.

The seed layer **614** is a bilayer with a first sublayer of tantalum

25 (Ta) having a thickness of 30 Å and a second sublayer of Ni-Fe

having a thickness of 10 Å deposited on the first shield layer 652. The first SV stack **608** is formed on the seed layer by sequentially depositing the AFM1 layer **616** of Pt-Mn having a thickness of about 160 Å, the ferromagnetic layer **618** of Co-Fe

5 having a thickness of about 12 Å, the APC layer **620** of ruthenium (Ru) having a thickness of about 8 Å, the ferromagnetic layer **622** of Co-Fe having a thickness of about 18 Å, the conductive first spacer layer **624** of Cu-O having a thickness of about 22 Å, and the first sense layer **625** of Co-Fe having a thickness of

10 about 18 Å. The first spacer layer **624** is formed by depositing a copper (Cu) film with DC-magnetron sputtering from a pure Cu target in a mixture of argon and oxygen gases of 2.985 and 0.015 mTorr, respectively, and then exposing to a mixture of argon and oxygen gases of 2.94 and 0.06 mTorr, respectively, for 4 minutes.

15 This optimum *in situ* oxidation is incorporated into this Cu-O formation process for reducing ferromagnetic coupling between the sense and pinned layers.

The longitudinal bias stack **610** is formed on the first SV stack **608** by sequentially depositing the first decoupling layer

20 **629** comprising a first sublayer **626** of Cu-O having a thickness of about 10 Å and a second sublayer **628** of ruthenium (Ru) having a thickness of about 20 Å, the FM1 layer **630** of Co-Fe having a thickness of about 24 Å, the AFM3 layer **632** of Ir-Mn having a thickness of about 60 Å, the FM2 layer **634** of Co-Fe having a

thickness of about 24 Å, and the second decoupling layer **633**

comprising a first sublayer **636** of ruthenium (Ru) having a

thickness of about 20 Å and a second sublayer **638** of Cu-O having

a thickness of about 10 Å. The Cu-O sublayers **626** and **638** are

5 formed by depositing a copper (Cu) film with DC-magnetron

sputtering from a pure Cu target in a mixture of argon and oxygen

gases of 2.985 and 0.015 mTorr, respectively, and then exposing

to a mixture of argon and oxygen gases of 2.94 and 0.06 mTorr,

respectively, for 4 minutes. The Cu-O films facilitate the sense

10 layers to exhibit good soft magnetic properties.

The second SV stack **612** is formed on the longitudinal bias

stack **610** by sequentially depositing the second sense layer **639**

of Co-Fe having a thickness of about 18 Å, the conductive second

spacer layer **640** of Cu-O having a thickness of about 22 Å, the

15 ferromagnetic layer **642** of Co-Fe having a thickness of about 18

Å, the APC layer **644** of ruthenium (Ru) having a thickness of

about 8 Å, the ferromagnetic layer **646** of Co-Fe having a

thickness of about 12 Å, and the AFM2 layer **648** of Pt-Mn having

a thickness of about 160 Å. The spacer layer **640** is formed by

20 depositing a copper (Cu) film with DC-magnetron sputtering from a

pure Cu target in a mixture of argon and oxygen gases of 2.985

and 0.015 mTorr, respectively, and then exposing to a mixture of

argon and oxygen gases of 2.94 and 0.06 mTorr, respectively, for

4 minutes. This optimum *in situ* oxidation is incorporated into

this Cu-O formation process for reducing ferromagnetic coupling fields between the sense and pinned layers. The cap layer **650** is a bilayer with a first sublayer of ruthenium (Ru) having a thickness of 40 Å and a second sublayer of tantalum (Ta) having

5 a thickness of 30 Å formed over the AFM2 layer **648**.

The second shield layer **654** formed of Ni-Fe having a thickness of 10000 Å is deposited over the cap layer **650**. An insulating layer **656** formed of Al_2O_3 deposited between the first shield layer **652** and the second shield layer **654** provides

10 electrical insulation between the shields/leads and prevents shunting of the sense current around the active region **602** of the dual SV sensor **600**.

After the deposition of the central portion **602** is completed, the SV sensor is annealed for 2 hours at 280° C in the

15 presence of a magnetic field of about 10,000 Oe in a transverse direction perpendicular to the ABS and is then cooled while still in the magnetic field to set the exchange coupling of the AFM1 and AFM2 layers **616** and **648** with the AP-pinned layers **617** and **641**, respectively, so that the magnetizations in the two

20 AP-pinned layers are perpendicular to the ABS with net magnetic moments canceling each other. This results in cancellation of the demagnetization fields between the the AP-pinned layers **617** and **641**.

After the first anneal, a second anneal is carried out for 2

hours at 240° C in the presence of a magnetic field of 200 Oe in

a longitudinal direction parallel to the ABS. Because the

blocking temperature of the Pt-Mn antiferromagnetic material (>

5 360° C) of the AFM1 and AFM2 layers is higher than 240° C, the

magnetizations of the first and second AP-pinned layers 617 and

641 are not rotated while the magnetizations 631 and 635 in the

longitudinal bias stack are oriented in the longitudinal

direction due to the lower (less than 240° C) blocking

10 temperature of the Ir-Mn antiferromagnetic material of the AFM3

layer. After the second anneal, the magnetization 631 of the FM1

layer 630 forms a flux closure with the magnetization 627 of the

first sense layer 625 providing stability for the first sense

layer 625. Similarly, the magnetization 635 of the FM2 layer 634

15 forms a flux closure with the magnetization 637 of the second

sense layer 639 providing stability of the second sense layer

639.

The Cu-O/Ru and Ru/Cu-O films are used as first and second

decoupling layers 629 and 633. Either one of the Cu-O or Ru

20 films is not used alone as a decoupling layer since strong

exchange coupling occurs across either film and full decoupling

can only be attained when the film thickness is far greater than

30 Å. In order to attain strong magnetostatic interactions from

the flux closures, the decoupling layer thickness is preferred to

be as small as possible, but not to be too small to induce the exchange coupling. The Cu-O film of the decoupling layers is adjacent to the Co-Fe sense layers to promote good soft magnetic properties. The Ru film of the decoupling layers is also used as

5   a seed layer for the Co-Fe/Ir-Mn/Co-Fe longitudinal bias layers to promote high unidirectional anisotropy fields (H_{UA}).

In this preferred embodiment, the Co-Fe/Ir-Mn/Co-Fe film stack is used for antiferromagnetic stabilization of the dual SV sensors. Alternatively, a Ni-Fe(10Å)/Co-Pt(40Å)/Ni-Fe(10Å) film

10 stack can be used to replace the Co-Fe/Ir-Mn/Co-Fe film stack for hard magnetic stabilization. The Ni-Fe film is adjacent to the Co-Pt film in order to reduce stray fields from the Co-Pt film and improve its squareness. In this alternate embodiment, the second anneal used to longitudinally orient the magnetizations of

15 the Co-Fe/Ir-Mn/Co-Fe stack is eliminated, but magnetic setting of the Ni-Fe/Co-Pt/Ni-Fe stack in a field of 3 kOe must be conducted at room temperature after the head fabrication process.

Second Example

20   Fig. 7 shows an air bearing surface (ABS) view, not to scale, of a CPP dual spin valve (SV) sensor **700** according to another embodiment of the present invention. The dual SV sensor **700** is the same as the dual SV sensor **600** shown in Fig. **6** except that in order to achieve a read gap thickness of 50 nm the AFM1

25 and AFM2 layers **616** and **648** have been eliminated and the AFM3

layer **632** of the longitudinal bias stack **610** has been replaced by

an AFM3 layer **716** of Pt-Mn having a thickness of 160 Å. The

dual SV sensor **700** comprises a first SV stack **708**, a second SV

stack **712** and a longitudinal bias stack **710** disposed between the

5 first and second SV stacks **708** and **712**. In this embodiment the

first SV stack **708** is the same as SV stack **608** without the AFM1

layer **616** and the second SV stack **712** is the same as SV stack **612**

without the AFM2 layer **648**. The longitudinal bias stack **710** is

the same as bias stack **610** with the AFM3 layer of Ir-Mn replaced

10 with an AFM3 layer **716** of Pt-Mn having a thickness of 160 Å.

The SV sensor **700** is fabricated in an integrated ion beam/DC

magnetron sputtering system to sequentially deposit the

multilayer structure shown in Fig. 7. The deposition process is

the same as the process used to fabricate the SV sensor **600**.

15 After the deposition of the central portion **602** is

completed, the SV sensor **700** is annealed for 2 hours at 280° C in

the presence of a magnetic field of 200 Oe in a longitudinal

direction parallel to the ABS. The magnetic field is higher than

the uniaxial anisotropy field H_K ($\leq$ 20 Oe) of the as-deposited

20 Co-Fe/Pt-Mn/Co-Fe films so that strong exchange coupling in the

Co-Fe/Pt-Mn/Co-Fe films can be developed in the longitudinal

direction parallel to the ABS during annealing. The magnetic

field is less than the spin flop field H_{SF} ($\geq$ 1 kOe) of the first

and second AP-pinned layers **617** and **641** so that strong

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antiparallel coupling across the Ru APC layers in the first and second AP-pinned layers **617** and **641** is not interrupted during annealing.

Although the Pt-Mn AFM layers are not used in the first and second SV stacks **708** and **712** to produce H_{UA} for transverse pinning, the transverse pinning can still be attained due to a strong spin-flop field (H_{SP}) induced from antiparallel coupling across the Ru APC layers. The transverse pinning can be further reinforced if the Co-Fe films adjacent to the Ru APC layers have a high intrinsic uniaxial anisotropy field (H_K) and a high positive saturation magnetostriction (λ_s). The high λ_s is needed to stress-induce a high extrinsic uniaxial anisotropy field (H_K'), determined from $H_K' = 3(\lambda_s/M_s)\sigma$ after sensor lapping. The $Co_{90}-Fe_{10}$ (in atomic %) commonly used for the ferromagnetic layers of the AP-pinned layers **617** and **641** has an H_K of 16 Oe. When the Fe content is increased to 20 at.%, H_K becomes 30 Oe and the λ_s increases to 35.1×10^{-6} (corresponding to 142 Oe). Hence, in this alternative embodiment, a Co-Fe film with an Fe content of 20 at.% or higher (up to 50 at.%) is preferably used for the ferromagnetic layers of the AP-pinned layers.

Although the total uniaxial anisotropy field $H_K + H_K'$ (172.5 Oe) is not as high as H_{UA} (600 Oe) and H_{SP} (900 Oe), it has two major unique features, leading it to play an important role in providing transverse pinning. First, $H_K + H_K'$ is determined only from the Co-Fe film itself, while H_{UA} and H_{SP} are determined not

only from the Co-Fe film, but also from its adjacent Ru and Pt-Mn films. As a result, the temperature dependence of $H_K + H_K'$ is determined by the Curie temperature of the Co-Fe film (~700 °C), while the temperature dependence of H_{UA} is determined by the

5 blocking temperature of the exchange-coupled Pt-Mn/Co-Fe films (~360 °C), and the temperature dependence of H_{SP} is determined by the critical temperature of the antiparallel-coupled Co-Fe/Ru/Co-Fe films. Since the Curie temperature is much higher than the blocking and critical temperatures, $H_K + H_K'$ can remain

10 nearly unchanged at elevated sensor operation temperatures (~180 °C). Thus $H_K + H_K'$ may play a crucial role in improving thermal stability. Second, $H_K + H_K'$ substantially reduces edge curling effects of magnetizations of the ferromagnetic films of the AP-pinned layers. The reduction in the edge curling effects

15 results in more uniform magnetization along the sensor height, therefore providing better flux closure to cancel magnetization more efficiently. Hence, even without the use of the Pt-Mn film for transverse pinning, the transverse pinning field resulting from H_{SP}, H_K and H_K' should be high enough for proper sensor

20 operation.

Third Example

Fig. 8 shows an air bearing surface (ABS) view, not to scale, of a CPP hybrid spin valve (SV)/magnetic tunnel junction

25 (MTJ) sensor **800** according to a another embodiment of the present

invention. The hybrid SV/MTJ sensor **800** is the same as the dual SV sensor **600** shown in Fig. **6** except that one of the two SV stacks **608** and **612** is replaced with a magnetic tunnel junction (MTJ) stack. In the embodiment shown in Fig. **8**, the second SV

5 stack **612** has been replaced with an MTJ stack **812**. However, alternatively, the first SV stack **608** may be replaced with an MTJ stack to form an alternative hybrid MTJ/SV sensor.

The SV/MTJ sensor **800** comprises an SV stack **608**, an MTJ stack **812** and a longitudinal bias stack **610** disposed between the

10 SV stack **608** and and the MTJ stack **812**. In this embodiment the SV stack **608** and the longitudinal bias stack **610** are identical to the first SV and longitudinal bias stacks of the preferred embodiment shown in Fig. **6**. The MTJ stack **812** deposited over the longitudinal bias stack **610** comprises a second sense layer **639**, a

15 nonconductive tunnel barrier layer **840**, a second AP-pinned layer **641** and a second antiferromagnetic (AFM2) layer **648**. Only the tunnel barrier layer **840** which replaces the conductive second spacer layer **640** of the SV sensor **600** is different from the layers forming the SV sensor **640**. The tunnel barrier layer **840**

20 of Al-O having a thickness of about 6 Å is formed on the second sense layer **639** by depositing an aluminum (Al) film with DC-magnetron sputtering from a pure Al target in an argon gas of 3 mTorr, and then exposing to an oxygen gas of 2 Torr for 4 minutes. This optimal *in situ* oxidation is incorporated into

this Al-O formation process for attaining a high tunneling

magnetoresistance and a low junction resistance. The second

AP-pinned layer **641** and the AFM2 layer **648** are sequentially

deposited on the tunnel junction layer **840** to complete the

5 fabrication of the MTJ stack **612**. All other processing steps are

identical to those described above with respect to fabrication of

the SV sensor **600**. The response of the hybrid dual SV/MTJ sensor

800 to an external magnetic signal is the sum of the response of

the SV stack **608** and the response of the MTJ stack **812**.

10   Alternatively, for the hybrid MTJ sensor **800**, the AFM1 and

AFM2 layers formed of Pt-Mn used in the first and second stacks

can be eliminated, and the Ir-Mn film used for AFM3 in the

longitudinal bias stack may also be replaced with a Pt-Mn film as

described in the second example.

15   While the present invention has been particularly shown and

described with reference to the preferred embodiments, it will be

understood by those skilled in the art that various changes in

form and detail may be made without departing from the spirit,

scope and teaching of the invention. Accordingly, the disclosed

20 invention is to be considered merely as illustrative and limited

only as specified in the appended claims.